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Literature review on solar adsorption technologies for ice-making and air-conditioning purposes and recent developments in solar technology

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Abstract

The primary objective of this review is to provide fundamental understandings of the solar adsorption systems and to give useful guidelines regarding designs parameters of adsorbent bed reactors,and the applicability ofsolar adsorption both in air-conditioning and refrigeration with the improvement of the coefficient of performance. Solar adsorption heat pump and refrigeration devices are of significance to meet the needs for cooling requirements such as air-conditioning and ice-making and medical or food preservation in remote areas. They are also noiseless, non-corrosive and environmentally friendly. For these reasons the research activities in this sector are still increasing to solve the crucial points that make these systems not yet ready to compete with the well-known vapor compression system. There is an increasing interest in the development and use of adsorption chillers due to their various economic and impressive environmental benefits, enabling solar energy or waste heat to be used for applications such as district networks and cogeneration plants. Compared to adsorption systems that require heat sources with temperatures above 100°C (zeolite–water systems, activated carbon–methanol systems) or conventional compressor chillers, a silica gel/water adsorption refrigerator uses waste heat with temperature below 100°C. This creates new possibilities for utilizing low temperature energy. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Solar adsorption; Air-conditioning; Adsorption chillers; Refrigeration; Ice-making

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Contents

1. Introduction

In the early years of this century, sorption refrigeration was frequently used, later with the development of cheap reliable compressors and electrical motors, the improvement in power station efficiency and the introduction of CFCs in the 1930s, sorption refrigeration became a niche technology [1].

Heat-driven sorption refrigeration cycles have existed in patent literature since at least 1909, and refrigerators were commercially available in the 1920s. In 1929, Miller described several systems which utilized silica gel and sulfur dioxide as an adsorbent/adsorbate pair [2].

However, recent years have witnessed increasing interest in this technology for many different reasons. The main arguments in favor are that sorption systems are quiet, long lasting, cheap to maintain and environmentally benign.

Refrigeration technology is required to evolve due to the new environmental regulation. The first regulation concerning the depletion of the ozone layer (Montreal protocol, 1988) decided to phase-out chlorofluorocarbons (CFCs) and then hydrochlorofluorocarbons (HCFCs). More recently adsorptive processes have been proposed for heat pump and refrigeration as consistent alternative to vapor compression systems. Ecological problems concerning the emission of CFCs from refrigerating units

have stimulated several theoretical and experimental studies on adsorption cooling systems.The environmental impact of fluorocarbon traces in the atmosphere has shown that CFC emissions are responsible for about one third the global greenhouse effect [3].

These trends bring to a strong exigence of new systems for space heating and cooling, with the possibility also to obtain a primary energy diversification. Among the proposed technologies, the solid sorption has a very good perspective, in fact, in addition to the non-polluting refrigerants, they can efficiently use natural gas or solar energy as primary energy and they have no moving parts, which makes the machine silent and with no maintenance needs. Therefore, adsorption heating and cooling can be a good alternative to classical vapor-compression machines. Adsorption cooling units are attractive since they can be operated at temperature levels where liquid absorption systems cannot work.

Adsorption is accompanied by evolution of heat. Also the heat of adsorption is usually 30–100% higher than that of condensation of the adsorbate. Thus, if a fresh adsorbent and adsorbate in liquid form coexist separately in a closed vessel, transport of adsorbate from the liquid phase to the adsorbent occurs in the form of vapor, since adsorption is stronger than condensation to liquid phase. During this step, the temperature of the liquid phase becomes lower while the adsorbent temperature rises. Air-conditioning and refrigeration utilize this phenomenon [4]. Solid/gas systems present the advantage of being absolutely benign for the environment: zero ODP (ozone depletion potential) as well as zero GWP (global warning potential). However, to become a realistic alternative, those systems must exhibit high enough performances to avoid an extra primary energy consumption. The figures of merit which are commonly used to characterize the performances of such cycles are the COP (coefficient of performance), the SCP (specific cooling power) and the thermodynamic efficiency which is the ratio between the COP and the Carnot COP. The use of solids for removing substances from either gaseous or liquid solutions has been widely used since biblical times. This process, known as adsorption, involves nothing more than the preferential partitioning of substances from the gaseous or liquid phase onto the surface of a solid substrate. From the early days of using bone char for decolorization of sugar solutions and other foods, to the later implementation of activated carbon (AC) for removing nerve gases from the battlefield, to today's thousands of applications, the adsorption phenomenon has become a useful tool for purification and separation.

Adsorption phenomena are operative in most natural, physical, biological, and chemical systems, and adsorption operations employing solids such as AC and synthetic resins are used widely in industrial applications and for purification of waters and waste water. The process of adsorption involves separation of a substance from one phase accompanied by its accumulation or concentration at the surface of another. The adsorbing phase is the adsorbent, and the material concentrated or adsorbed at the surface of that phase is the adsorbate. Adsorption is thus different from absorption, a process in which material transferred from one phase to another (e.g. liquid) interpenetrates the second phase to form a 'solution'. The term sorption is a general expression encompassing both processes. As explained by many authors

including Ponec, Oscik, Ruthven and Suzuki 'physical adsorption' is a surface phenomenon caused mainly by van der Waals forces and electrostatic forces between adsorbate molecules and the atoms which compose the adsorbent surface. However, regardless of the type of sorption involved, all involve evolution of heat of adsorption. Adsorbent substances can be restored to original conditions by a desorption process usually involving the application of heat. Thus adsorbents are characterized first by surface properties such as surface area and polarity. A large specific surface area is preferable for providing large adsorption capacity, but the creation of a large internal surface area in a limited volume inevitably gives rise to large numbers of small sized pores between adsorption surfaces. The size of the micropores determines the accessibility of adsorbate molecules to the internal adsorption surface, so the pore size distribution of micropores is another important property for characterizing adsorptivity of adsorbents. Especially materials such as zeolite and carbon molecular sieves can be specifically engineered with precise pore size distributions and hence tuned for a particular separation. Depending upon adsorbent and adsorbate phases, adsorption systems may be classified as solid/gas, liquid/gas, solid/liquid, and liquid/liquid [5]. Surface polarity corresponds to affinity with polar substances such as water or alcohols.

Polar adsorbents are thus called 'hydrophillic' and aluminosilicates such as zeolites, porous alumina, silica gel or silica–alumina are examples of adsorbents of this type. On the other hand, no-polar adsorbents are generally 'hydrophobic'. Carbonaceous adsorbents, polymer adsorbents and silicalite are typical non-polar adsorbents. These adsorbents have more affinity with oil or hydrocarbons than water. In this review we have paid great attention on physical adsorption which is more suitable for refrigeration and air-conditioning applications.

According to the information gathered from literature, much research has been performed on sorption refrigeration. In general there are two broad categories of these adsorptive systems: intermittent and continuous. Intermittent systems include solar-powered, daily-cycled systems [6]. In this present review most attention has been focused on the intermittent cycles due to the limiting conditions imposed by the use of solar adsorption.

2. Refrigerants and adsorbents and comparison between various solid adsorbent pairs

One of the most important elements of any heat pump and refrigeration system is the refrigerant, since the working pair conditions and compatibility with the environment principally depend on it. Generally speaking, the refrigerant requirements are: high latent heat per unit volume; and good thermal stability. Briefly, adsorption characteristics of adsorbents are determined by the adsorption isotherms, for the amount of a substance adsorbed.

Solar adsorption refrigeration ice-making systems are greatly influenced by the properties of the adsorption pair. For small temperature lifts ($\Delta T < 30°C$) the COPs are higher for a number of adsorption pairs; similar conclusion has been put forward

by Passos et al. [6]. The zeolite–water pair would be better than the active carbon pairs for large temperature lifts ($\Delta T>40°C$), but as water freezes under 0°C, in the range $T_{ev}<0°C$ it cannot be used. The zeolite–water pair requires high regenerating temperatures (≅170°C), whereas the active carbon pair can be operated at low regenerating temperatures.

Various studies have developed detailed models and examined the suitability of various desorbent/adsorbate pairs for solar cooling applications. Aceves [7] studied the performance of an adsorption cooling system for electric vehicles. The second category is multiple bed, continuous cooling systems. These allow for greater applicability due to the continuous cooling as well as the potential for efficiency enhancement through heat regeneration.

Differential heats of adsorption for some adsorbent/adsorbate pairs are given in Table 1. The suitable adsorbents are porous materials that should adsorb a large amount of refrigerant fluid in the vapor phase and present some additional characteristics: wide concentration change in a small temperature range; reversibility of adsorption process for many cycles; low cost; good thermal conductivity.

Appropriate working pairs are zeolite–water, zeolite–organic refrigerants, silica gel–water, salts–ammonia (ammoniated salts), AC–methanol, metal–hydrogen (metal hydrides) and some other materials in solid sorption systems, as well as ammonia–water or water–lithium bromide in liquid sorption systems, amongst others.

Among all these combinations of adsorbents and adsorbates silica gel–water, AC–ammonia (methanol), zeolite–water and calcium chloride–ammonia have been used in adsorption refrigeration systems utilizing solar energy for the regeneration of the adsorbent bed.

Units working with an AC–methanol pair had been used in the 1930s and recently this pair has been tested for solar cooling applications.

3. Solar adsorption cooling alternatives

3.1. Solar technologies available

In order to evaluate the potential of the different solar cooling systems, a classification has been made by Best and Ortega [8]. It is based on three main concepts: solar collectors technologies; technologies for cold production; and specific uses. The solar technologies considered relevant are:

- flat plate collectors;
- evacuated tubes;
- stationary non-imaging concentrating collectors such as CPC;
- dish type concentrating collectors;
- linear focusing concentrators;
- solar ponds;
- photovoltaic systems; and
- thermoelectric systems.

Table 1
Heat of adsorption of some adsorbent/adsorbate pairs extracted from [5]

	Adsorbate	Heat of adsorption (kJ/kg)	Density of the adsorbate (kg/m^3)	Application area
Activated alumina	H_2O	2800	1000	Used mostly for desiccant cooling
	H_2O	3000		Water is perfect,except for very low operating pressure
Zeolite (various grades)	H_2O	3300–4200		Natural zeolites have lower values than synthetic zeolites
	NH_3	4000–6000	681	
	CO_2	800–1000	–	
	CH_3OH	2300–2600	791	
Silica gel	Methyl alcohol	1000–1500	703	Not suitable above 200°C
			789	
Charcoal	C_2H_4	1000–1200		Reacts at ca 100°C.Ammonia and methanol are not compatible with copper at high temperature
	NH_3	2000–2700		
	H_2O	2300–2600		
	CH_3OH	1800–2000		
	C_2H_5OH	1200–1400		
Calcium chloride	CH_3OH			Used for cooling
Metal hydrides	Hydrogen			For air-conditioning
Complex compounds	Salts and ammonia or water			Refrigeration

Nevertheless, so far, the market price for these collectors (per energy unit) is too high to be competitive with electrical power or natural gas. Moreover the collector efficiency decreases significantly with increasing collector temperature. Unfortunately, until now, for use with most cooling technologies, temperatures near 100°C are required. The success of solar cooling is strongly dependent on the availability of low cost and high performance of solar collectors.

The CPC collector has a high output energy and efficiency in the winter months than the flat plate collector under the same conditions. Otherwise the flat plate is more efficient due to the higher heat transfer coefficient of the flat plate than the CPC and evacuated tube collectors. Under a low solar intensity and a low ambient temperature, the output energy from all collectors is much decreased.

Costs are a bit lower for flat plate collectors with liquid heat carrier than for solar air collectors; the main reason is that at temperatures required for air-conditioning the flat plate collectors exhibit higher efficiencies.

Recent advances in solar energy and cooling system technologies make it feasible to convert sunlight into cooling power at net coefficients of performance reaching, and exceeding 100%. The net solar COP is currently in the range of 0.3–0.6 (with

optimistic future improvements). A major leap has been realized in the net COP for solar cooling by introducing solar fiber optic mini-dish concentrators that offer a significance increase in collection efficiency while retaining the possibility of high-temperature delivery. The fiber-optic mini-dish satisfies many criteria at costs that should be less than or comparable to current high-concentration solar alternatives [9]. An additional attractive element of mini-dish systems is modularity: being able to realize practical compact cooling plants with relatively small installed capacities. This new technology can be useful to overcome the inherent limitations for adsorption chillers applications.

3.2. Solar adsorption refrigeration systems for ice-making

The cooling technologies are:

- continuous adsorption;
- intermittent adsorption;
- solid/gas adsorption;
- diffusion;
- absorption; and
- desiccant systems.

Solar refrigeration is an important use of solar energy because the supply of solar energy and the demand for cooling are greatest during the same season. It has the potential to improve the quality of life of people who live in areas where the supply of electricity is far from sufficient. It is intended to be applied to the storage of agricultural, products food and medicines (e.g. vaccines) in remote areas and developing countries. The solar powered solid adsorption refrigeration system is one of the most promising technology because it is environmentally friendly with low cost, high efficiency, simple manufacture and low maintenance requirements. Also, solar energy is more and more recognized as a priority in developing countries (UNEP report, 1997 [10]).

Several adsorptive solar cooling units have been successfully tested by various authors in recent years. One of the very effective forms of solar refrigeration is the production of ice, because, ice accumulates much latent heat, thus the volume of ice-maker can be small. A demonstration unit of a refrigerator was first commercialized by Tchernev [40] by using zeolite–water system. Guilleminot (1980) suggested the feasibility of utilizing the principle in adsorption-cooling system from the view point of thermodynamics. R.E. Critoph presented performance limitations of adsorption cycles for solar cooling.

In the field of adsorptive systems, different types of solid–gas pairs were studied to build adapted cooling solar systems. At LIMSI, the zeolite–water pair was chosen [23] for refrigeration, and the active carbon–methanol pair for ice production [41]. Pons and Grenier [42] worked on a solid adsorption pair of zeolite and water, to produce a refrigerating effect and the coefficient of performance was about 0.1. In 1986, they successfully experimented with the adsorption pair of AC and methanol.

Similar work was carried out by Exell et al. [43] employing a flat plate collector which consists of an array of 15 copper tubes. Sakoda and Suzuki [30], utilizing solar heat, presented the advantages and limitations of the simultaneous transport of heat and adsorbate in a closed type adsorption cooling system. In Fig. 1, it is shown a schematic of an adsorptive solar powered ice-maker which is an extension of a previous model in order to study the daily ice production sensitivity with respect to various parameters of units.

These units are mainly composed of a single glassed collector-condenser connected by a flexible tube with an evaporator. The collector-condenser (1 m^2, 99 mm thick, 20° tilted) is made of two identical stainless steel shells. A grid holds 20 kg of AC in the upper shell, which plays the role of solar collector. The outside face of the solar collector is covered by selective surface. The rear shell of the collector-condenser plays the role of air cooled condenser with external fins (7.5 m^2). The packaged component, collector-condenser, represents the main new feature of these units [11].

The evaporator (0.3 m^2) is made of steel, immersed in a highly insulated, 5.2 l, ice-making box. A combined solar refrigeration and power system offers several advantages over a pure refrigeration system alone. A complete system utilizing solar energy for both heating and cooling is shown in Fig. 2.

Here the condenser and evaporator are combined into a single unit that is cooled by an external water loop. During the day water vapor desorbed from the solar heated zeolite is condensed in this unit, and the heat of condensation is rejected to the external water loop. This heat can be used for providing domestic hot water and during the winter season for space heating as well. During the heating season hot water is stored during the day to provide heat during the night, as in the conventional solar system. Whenever there is a demand for heat, hot water from the storage tank is circulated through a coil located in the air ducts of the forced air system, and the

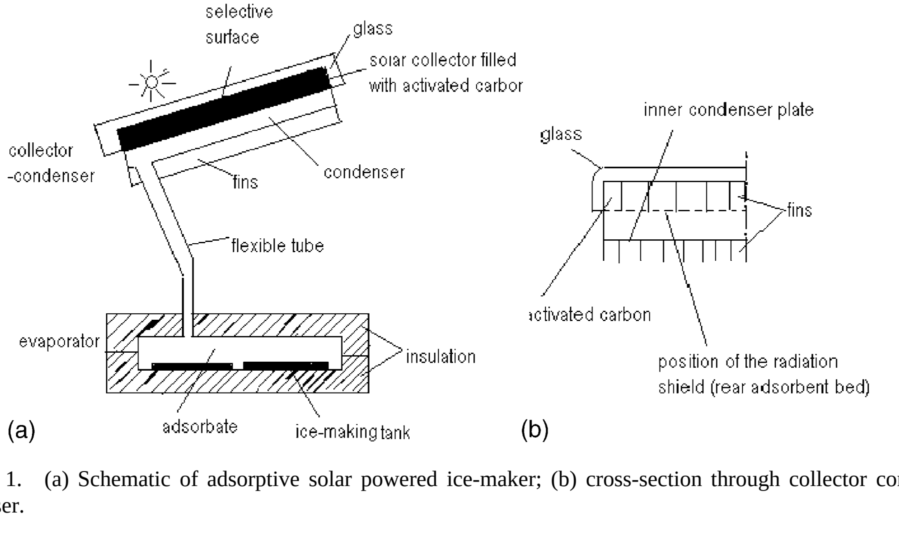

Fig. 1. (a) Schematic of adsorptive solar powered ice-maker; (b) cross-section through collector condenser.

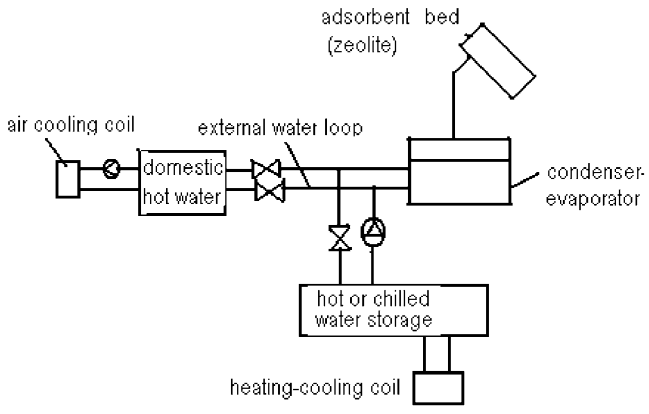

Fig. 2. Zeolite system for heating and cooling [12].

heated air is distributed throughout the building. If too much heat is liberated in the condenser, as for example in the spring and summer, the excess can be rejected to the outside by an air-cooled coil.

During the night, water in the condenser–evaporator unit evaporates from the same surfaces on which it originally condensed and the vapor is adsorbed on the cool zeolite. The external water loop provides the necessary heat of vaporization, producing chilled water for use in air-conditioning. The chilled water can be stored during the same summer season in the same storage tank used for hot water during the heating season. The changeover from one season to the other is achieved by simple valving.

A new hybrid system of solar powered water heater and adsorption ice-maker using the pair AC–methanol, has been studied by Wang [13] and the schematic of the system is presented in Fig. 3.

The working principle is a combination of a solar water heater and an adsorption refrigeration. The heating process is started in the morning through a vacuum tube solar collector. With the increase of water temperature, the adsorbent bed temperature rises. When the temperature in the adsorbent rises up to a temperature which causes the vapor pressure of the desorbed refrigerant to the condensing pressure. This liquid flows to the evaporator via a receiver. This liquid flows to the evaporator through a flow rate regulating valve. The temperature of the water and the adsorbent bed temperature continue to rise due to solar heating until the regeneration temperature reaches 80–100°C. With a 2 m^2 solar collector and 60 kg of water at 90°C, the adsorption system can produce 10 kg ice per day.

In order to increase the desorption temperature and have a good cooling effect during the adsorption period at night, Headley et al. [44] constructed a charcoal–methanol adsorption refrigerator powered by CPC concentrating solar collectors, but the solar COP was very low (about 0.02). Table 2 shows some realized adsorption machines.

In China, Li et al. [45] constructed a solar ice-maker with the absorption pair of

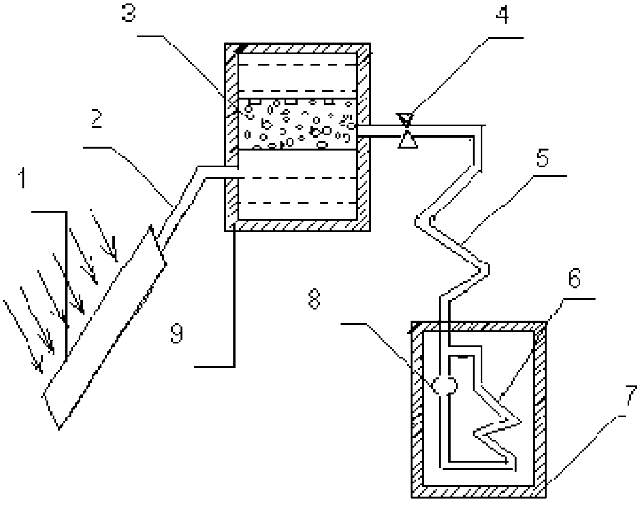

Fig. 3. Schematic of the solar water and refrigerator. (1) Solar collector, (2) water pipe, (3) adsorber, (4) valve, (5) condensor, (6) evaporator, (7) refrigerator (with cold storage), (8) receiver, and (9) hot water container.

ammonia and water. With the exposed collector area of 1.5 m^2, daily ice production reached 6.8–8 kg, and the solar COP of the system was 0.105, Lin et al. [46] designed a solid absorption ice-maker using calcium chloride–ammonia, which could produce ice of about 3.5 kg/day, with exposed collector area of 1.6 m^2. Wang et al. [47] presented a new hybrid of solar powered water heater and adsorption ice-maker with a solar collector area of 2 m^2 which can produce 3–8.7 kg ice/day. The COP was about 0.15–0.23 and heating efficiency of about 0.35–0.38. In 1999, Wang et al. [48] carried out a study on solar adsorption ice-maker and the experimental results were very good and reached a COP of 0.12–0.135.

Units working with an AC–methanol pair had been used in the 1930s and recently this pair has been tested for solar cooling applications. In Table 2, it is shown that solar adsorption machines can be successfully realized.

The powered solid adsorption refrigeration system is the most promising technology because it is environmentally friendly with low cost, high efficiency, simple manufacture and low maintenance requirements.

The aim of this work is to make a review on solar solid sorption refrigerators and heat pumps using physical adsorption. The concept of solar-powered refrigeration has been analyzed by Cohen and Kosar and several machines operating on this principle are now commercially available. However, there has been little research into the integration of solar power with electricity, or natural gas.

Such a system could remain operational when solar insolation is low, continuing its all-year-round operation and use in areas where solar energy alone is impractical. Many solar powered domestic water heating systems have provision for an electrical one-person heater as a back-up. Use of a gas/electricity system would be more econ-

Table 2
Characteristics of some realized adsorption machines [14]

Authors	Adsorption pair	Solar collector	Condensation temperature (T_c, °C)	Evaporation temperature (T_{ev}, °C)	Regeneration temperature (T_g, °C)	Coefficient of performance (COP)	Utilization	Reference
Meunier et al. (1990); Meunier and Hischler (1979)	LH+methanol DEG+methanol	Steel cylindrical container H=0.4m	30, T_a=25°C	−5	70 145	0.33	Production of ice	The D–A model was used for COP
	PKST+methanol AC35–3+methanol BPL+methanol NORIT RB+methanol					0.33 0.33		
Meunier et al. (1979)	Zeolite 13x+water		30 50	5 5	70 150	Varies with T		The D–R model is used for COP
Meunier (1984); Meunier et al. (1979)	Zeolite 13x–methanol	Container in copper 0.5m² T_a=20°C	T_c=30°C, T_a=20° C	−10	Various			Eight lumps
	Zeolite–water AC35–methanol							
Pons and Guilleminot (1986)	AC–methanol	Flat plate collector of 6m²	T_c=T_a=25°C	T_e=−5°C	T_g=110°C	0.12	30–35 kg/d	Solar energy
Grenier et al. [24]	NaX zeolite–water	Solar collector of 20 m²	T_c=32	T_e=1	T_g=118°C	0.105 energy	7 kg/ m²	Solar D–R
Meunier (1984); Meunier et al. (1979)	Zeolite 13X+water	Copper box 0.89 m	26 31	0 0	91 11	0.14 0.095		
		0.89 m 0.89 m	48	0	121	0.04		

(continued on next page)

Table 2 (*continued*)

Authors	Adsorption pair	Solar collector	Condensation temperature (T_c, °C)	Evaporation temperature (T_{ev}, °C)	Regeneration temperature (T_g, °C)	Coefficient of performance (COP)	Utilization	Reference
William et al.; Meunier et al. (1979)	NH_3–H_2O			3	120	<0.32		Solar energy
Meunier (1986)	LiBr		20	-5	40			
	Z13X		30	−10	150			
	Z4AX–Water							
Critoph et al. (1987); Critoph (1988); Critoph and Vogel (1986)	Z5A	Steel tubes	30	−10	From 70 to 140		Production of ice	Electricity with D–R model
	Z13X							
	AC2207C+R11					0.13		
	R12					0.19		
	R22					0.15		
	R114					0.50		
	AC+Meth.							
Simonot-Grange and Guilleminot (1994)	Z4A–H_2O	Stainless steel tubes						The D–R model is used
	Z13X–methanol							
Tchernev [12]	Zeolite–water	Flat plate collector 2.44 m 1.2 m	40				100 kg/day	Solar energy
Tchernev [12]	Zeolite–water	Flat plate	40		15		To store 60 liters of milk	Solar energy
		1.5 m^2						

(continued on next page)

Table 2 (*continued*)

Authors	Adsorption pair	Solar collector	Condensation temperature (T_c, °C)	Evaporation temperature (T_{ev}, °C)	Regeneration temperature (T_g, °C)	Coefficient of performance (COP)	Utilization	Reference
Meunier (1986); Meunier et al. (1979)	Zeolite–water	Metallic box (2 m^2) with 0.065 m	<43		4		Refrigerator	Solar energy
Bougard (1986)	Activated carbon–ammonia	Finned tubes	20		-5			Solar energy
		ϕ=53 m L=0.2 m						
Tchernev [12]	Z13X–water	Surface area of 1 m^2	40	0	120	0.15	Air conditioning	
Trombe and Foex (1982)		Cylindro-parabolic	25					Solar energy
		1.5 m^2 and 1.8 m^2					4 kg/m^2 5 kg/m^2	
Sakoda and Motoyuki	Silica gel–water	0.25 m^2	35	5	100			Solar heat
Wang et al. [13]	Shanghai YKAC–methanol	Adsorber stainless steel, T_a=19.5°C, 2 m^2	15	-10	87	0.046	8 kg/day	Solar heat
Sumathy et al. [15]	AC–methanol	0.92 m^2	35	-6	100	0.1–0.12	4.5 kg/day	Solar heat

omical and utilizing gas/electricity and solar power simultaneously would reduce the cost and size of solar collectors employed in solar driven adsorption systems.

A solid sorption refrigerator with a day/night cycle to produce ice using solar energy was demonstrated by Guilleminot et al. [49]. Performance limitations of adsorption cycles for solar cooling were formulated by Critoph. Bougard and Veronikis used an ammonia/AC solid sorption machine as solar refrigerator. Vassiliev tested thermal control system for the solar solid sorption machines. A prototype of a solar powered cooling unit with ammonia and different salt was discussed by Speidel [16,17].

Numerical simulations and experimentation have been used to study the performance of an adsorptive solar refrigerator functioning with AC–methanol and zeolite–water. In 1992, Lemmini et al. [50] presented the performance simulation of adsorptive solar cooling units (performance comparison for two types of AC) to show that AC40–methanol can improve the COP over to 20%. A modelization of a solar powered solid adsorption cooling machine has been presented by Passos et al. [6] to conclude that the performance of the solar powered unit depends strongly on the absorptivity of the solar collector and on its back insulation. In 1986, Guilleminot et al. [49] carried out a study on heat and mass transfer in a non-isothermal fixed bed solid adsorbent reactor:a uniform pressure non-uniform temperature case.

Although this system has interested several laboratories, it has some disadvantages due to the fact the apparatus is inconvenient in certain respects. The intermittent and varying character of the operating conditions make the problems of cold compartment, thermal regulation, energy storage and automatic operation difficult to solve.

A combined solar refrigeration and power system offers several advantages over a pure refrigeration system alone. Excess cooling capacity can be reduced and power generation increased, thereby allowing the system to run continuously at maximum efficiency. A combined refrigeration and heating system could be operated to provide refrigeration and a salt water desalinization, refrigeration and drying, refrigeration and cooking, or refrigeration and heating. Lastly there is possibility of combining refrigeration, heating and electricity production.

Photovoltaic electricity generation can be also joined together with refrigeration production and be used to power other building services, such as lighting or ventilation, or it may be used to power up an energy storage to supplement the natural gas supply. It is interesting to consider a combined refrigeration and power generation system with short cycles: this which would allow the operation of systems requiring power for valve operation. A combined system would allow unencumbered operation.

Recently, as an internal experimental work, a solar adsorption air-conditioning system has been setup in our laboratory with the working pair of zeolite 13X–water. The results of the study show that if the system can reach a regeneration temperature of 110°C by using a two glass cover. It has been proved that the COP of the system depends strongly on the thickness of adsorbent bed layer (Fig. 4).

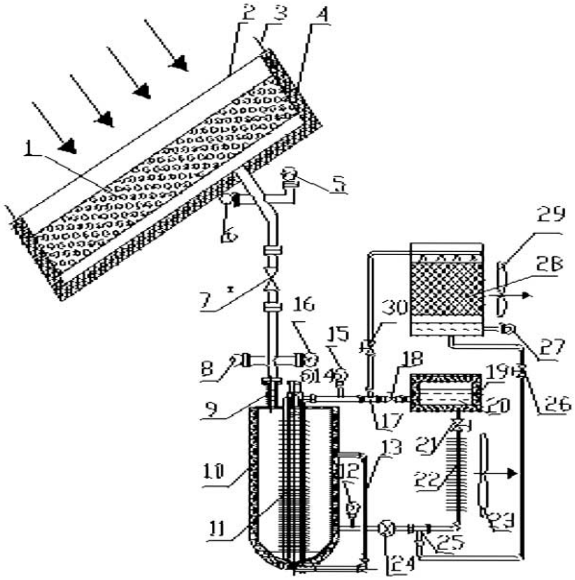

Fig. 4. Schematic representation of a solar adsorption air-conditioning. (1) Adsorbent bed, (2) glass cover, (3) inlet cooling water, (4) insulation material, (5) pressure gauge, (6) thermocouple, (7) valve, (8) thermocouple, (9 and 10) condenser, (11) evaporator, (12) temperature measurement, (13) liquid level tube, (14) thermocouple, (15) thermocouple, (16) pressure gauge, (17) three-way valve, (18) valve, (19) insulation, (20) water container, (21) valve, (22) heat exchanger, (23) ventilator, (24) vacuum pump, (25) three-way valve, (26) valve, (27) thermocouple, (28) cooling tower, (29) ventilator, (30) valve, (31) outlet cooling water.

3.3. Solar desiccant cooling and air-conditioning systems

In 1848 Faraday observed the cooling effect obtained by adsorbing ammonia into silver chloride and in the 1920s sulfur dioxide and silica gel were used for the air-conditioning of railway carriages in the USA. Recently, new adsorbates such as butane and R32 have been tested and manufactured by ICI. Also, a monolithic carbon block has been produced and tested by Sutcliffe Speakman Carbon using a 208C precursor, and a PVDC-based carbon block supplied by D. Quinn of the Royal Military College of Canada [18].

Desiccant technology has become a valuable tool in the industry's arsenal of space-conditioning options. In certain cooling applications, desiccant cooling units provide advantages over the more common vapor-compression and absorption units. For example, desiccant units do not require ozone-depleting refrigerants, and they can use natural gas, solar thermal energy, or waste heat, thus lowering peak electric demand.

The use of air-conditioning and refrigeration is increasing day by day for providing thermal comfort in industrial and residential areas. This technology requires energy

consumption and responsible for the emission of CO_2 and other greenhouse gases such as CFCs, HCFCs, which are considered to be major ozone-depleting gases.

Recent research in the development of a solar desiccant cooling system has focused on the development of advanced desiccant materials that give improved sorption capacity, favorable equilibrium isotherms, and better moisture and heat rates. Improved performance of these systems will lower their initial costs and make these systems a more attractive alternative to existing vapor compression systems. An improved system with Type 1M isotherm shape (modified Langmuir Type 1) has been proposed by Collier et al. [51]. Further development of such a system were continued by Belding et al. [52] and Worek et al. [53]. The suitability of different technologies for binding silica gel particles has been investigated [19].

In air-conditioning in order to improve the indoor air quality, solar solid desiccants and liquid desiccants are still used because they are also environmentally friendly. A new idea of passive-solar cooling using a desiccant material was developed by Fairey et al. (1986) and Swami et al. (1990). This concept, called a desiccant enhanced nocturnal radiation (DESRAD), utilizes a desiccant bed integrated in the roof along with a conventional vapor compression system to achieve both latent and sensible cooling in hot and humid climates. In this system, sensible cooling is provided during the night and the desiccant is regenerated during the day by solar heat. The system operates in two modes: adsorption mode; and daytime desorption mode. During the night, air is circulated to the desiccant bed on the roof where the moisture is removed. The heat of sorption is transferred to the atmosphere. After the air passes through the desiccant bed, it goes through an evaporative cooler to increase the humidity level and to further cool the air. This air is then passed into the conditioned zone where it absorbs both the heat and moisture from the space. The process of attracting and holding moisture is described as either adsorption or absorption, depending on wether the desiccant undergoes a chemical change as it takes on moisture. Adsorption does not change the desiccant except by the addition of the weight of water vapor, similar in some ways to a sponge soaking up water. Desiccants are subset of sorbents — they have a particular affinity for water.

An open-cycle desiccant cooling operating in a recirculating mode is shown in Fig. 3.

With respect to the use of solar energy the regeneration step is especially important: the regeneration, of course, can be performed directly by solar energy. Current interest, however, concentrates more and more on using the waste heat chillers for that purpose.

The solar-assisted desiccant cooling consists of the following major components in order to condition the process air to the desired comfort conditions:

1. a rotary wheel impregnated with a nominal silica gel matrix rotating continuously between the process and regeneration air streams;
2. a sensible heat wheel (rotary regenerator) also rotating between the process and regeneration air stream (the wheel transfers heat from the process side to the regeneration side);
3. process and regeneration side evaporative air coolers;

4. a solar collector storage subsystem for supplying the required thermal energy for regeneration;
5. a gas fired auxiliary heater as a backup for the solar subsystem;
6. a liquid-to-air heat exchanger coil; and
7. two thermostats one for activating the desiccant system and the other for activating the vapor compression system.

Hybrid systems, which integrate desiccant dehumidifiers with conventional cooling systems are proven to provide substantial energy savings. The necessary energy can be supplied by low temperature heat sources for the regeneration if the rotary dehumidifier matrix is properly constructed and appropriate selections are made for the type and amount of the desiccant. The thermal energy can be provided by a combination of an array of solar flat plate collectors and natural gas, as proposed by Davanagere et al. [20].The design of the air-conditioning cycle is controlled by many operating conditions. Referring to Fig. 3, the following parameters may be used as a basis for designing the system: ambient conditions; inside (room) conditions; regeneration air temperature before the dehumidifier; supply and return air flow rates; and design sensible and latent cooling loads.

Combinations of sorptive dehumidification with a conventional, electrically driven backup system allow for primary energy savings to 50% at low increased overall costs. This track seems to be worthwhile for future research and demonstration projects.

4. Thermodynamics of adsorption cycles

Thermodynamically speaking, adsorption cycles systems have been widely described by Cacciola and Restuccia [27] in the literature and the performances have been either theoretically or experimentally assessed. The thermodynamic efficiency of the adsorption heat pumps is much lower than that of the conventionally employed compression heat pumps. For this reason, the adsorption heat pumps are generally suitable for the employment of energy sources that are of trivial economic importance, such as waste heat and solar energy.

According to Polanyi theory [21] the adsorption equilibrium relation for a given adsorbent/adsorbate system can be expressed independent of temperature by using the adsorption potential (ε). Thus

$$\varepsilon = RT \ln\left(\frac{Ps}{P}\right)$$

where Ps is the saturated pressure of liquid adsorbate at the adsorption temperature T, and P is the pressure of the adsorbate vapor in equilibrium with the adsorbed liquid film, and R is the universal gas constant.

To describe the thermodynamic equilibrium of adsorption, several state equations known as isotherms adsorption are proposed. These function correlate the tempera-

ture T, the pressure P and the concentration of the adsorbed phase x, so that $f(T, P, x)=0$.The main isotherms of adsorption are:

1. Henry's law, valid for weak concentrations;
2. Langmuir's approach, which considers adsorption in monomolecular layers and that there is a dynamic equilibrium between the phases;
3. Gibb's theory based on the perfect gas equation, in which the adsorbate is treated in microcospic and bidimensional form; and
4. adsorption potential theory, based on a model originally proposed by Polany by the end of the 1920s, which is a purely thermodynamic approach, suitable for adsorption in microporous materials.

A detailed analysis of the thermodynamics of adsorption and its different isotherms are given by Leite [22]. For the equilibrium of adsorption in microporous materials with a polymodal distribution of pore dimensions, such as the AC-methanol pair Dubinin and Astakhov proposed the following isotherm:

$$X = Wo\rho_1(T)\exp\left\{-D\left[T\ln\left(\frac{Ps}{P}\right)\right]^n\right\}$$

where a is the adsorbed mass per unit of adsorbent mass, Wo the maximum adsorption capacity (volume of adsorbate/mass of adsorbent), ρ_1 the specific mass of adsorbate in the liquid state, D is the coefficient of affinity and n is characteristic parameter of the adsorption pair. This equation is adequate for many engineering applications of low grade heat especially those concerning solar energy.

The principal difficulties related with the thermodynamics of the basic adsorption cycle are as follows:

- intermittence of energy supplied to the user; and
- variable temperature of heat during the adsorption phase.

Many efforts have been made in different directions to obtain a cycle in which the output energy is both released continuously to the user and is within a small range of temperature variation. This goal is obtained by 'regenerative cycles' in which at least two reactors operate out of phase with internal heat recovery. Using the regenerative cycle, an improvement of COP is also obtained. However, this goal cannot be fulfilled by means of solar energy due to the limited regeneration temperature and the varying operating conditions. In order to practically obtain the proposed regenerative cycles, the principal recommendation is to improve the thermal conductivity of the solid adsorbent. Lots of practical and theoretical research have been carried out in recent years and the results revealed that more attention has to be paid to the optimization of these systems by reducing the number of valves and to produce simple and cost effective devices.

The principle of an adsorption cooling system is described in Fig. 5 by the Clapeyron diagram ($\ln p$ vs $-1/T$). The system is built up with a condenser, a throttle valve, and an evaporator and the adsorbent bed as thermal compressor (Fig. 6).

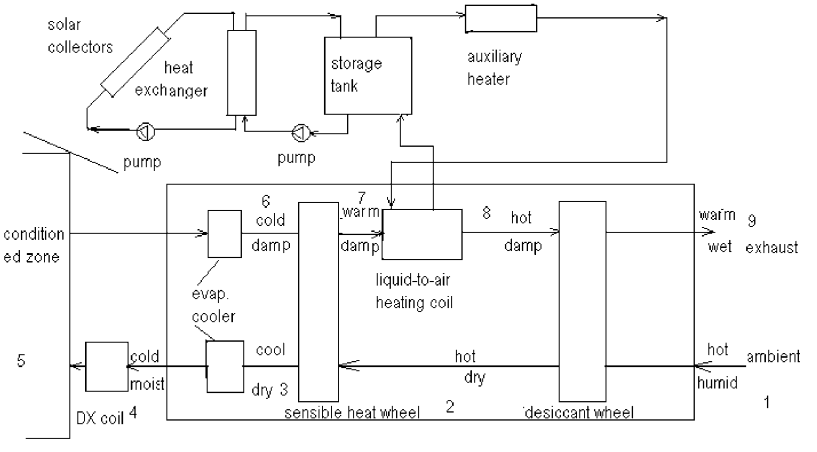

Fig. 5. Schematic of a solar-assisted desiccant cooling system.

The performance of the adsorption system depends on the relationship between Δx (difference of amount adsorbed between before and after regeneration) and T_g. Generally it is desirable to obtain a large amount of Δx at low levels of T_g.

The thermal compressor is operated in two phases. During the first phase of the operation cycle the refrigerant is evaporated at low pressure and low temperature in the evaporator and is adsorbed by the adsorbent under isobaric conditions. After the saturation, the adsorbent is regenerated by an isoteric heating of the adsorbent and a following isoteric desorption. In Fig. 2 the condenser and evaporator are combined into a single unit that is cooled by external water loop. During the day water vapor desorbed from the solar-heated zeolite is condensed in this unit, and the heat of

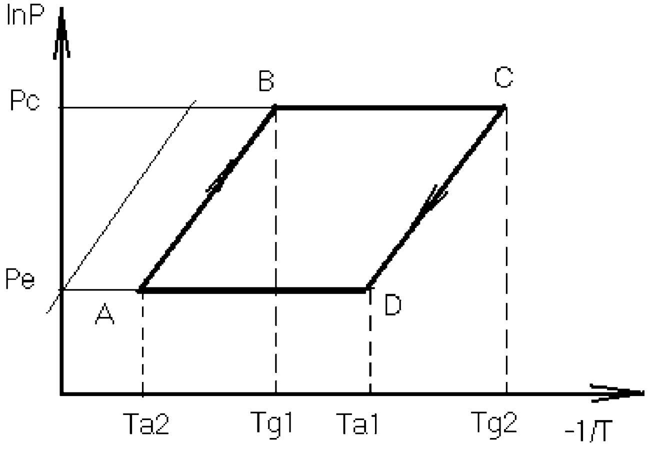

Fig. 6. Adsorption cycle in the Clapeyron diagram. In this diagram T_{a2} represents the temperature at the end of adsorption; T_{a1} is the temperature at start of adsorption; T_{g1} is temperature at start of regeneration; and T_{g2} represents the temperature at the end of desorption process.

condensation is rejected to the external water loop. This heat can be used for providing domestic hot water and during the winter season for space heating as well. During the heating period hot water is stored during the day to provide heat during the night as in any conventional system.

5. Heat and mass transfer inside the solar adsorption collectors

In spite of the long duration of a solar adsorption heat pump cycle there exists much evidence indicating the presence of temperature inhomogenities in the conventional solar collector. As a result of a various experimental studies, it has been determined that the temperature measured at the lower end of the solar collector generally remains well below the one measured at the upper end and the average temperature of the adsorbent is usually found to be to the former one [23,24]. Differences up to 30°C have been observed between the average temperature of the adsorbent and the temperature of the metal plate placed at the upper end of the solar collector. The fact that the condensation of the adsorbate may go on for a few additional hours after the maximum temperature has reached in the system, also indicates the existence of a thermal gradient in the collector.

An arrangement involving zeolite coatings synthesized on metal gauzes was recently proposed in order to remove any limitations originating from the existence of temperature and concentration gradients within the solar collector [25].

The possibility of decreasing cycle times in adsorption heat pumps drew attention to the limiting factors of the system. Improving the efficiency of transfer inside the machine and finding an economic compromise between mass and heat transfer are the crucial points to be considered.

Heat transfer problems in adsorption cycles systems have been intensively investigated by Cacciola and Guilleminot et al. [54]; the experience shows that two main resistances dominate the transfer of heat the external thermal vector fluid to the adsorbent bed:

- the first one occurs at the metal–adsorbent interface and depends on the physical contact between the materials; and
- the second resistance is associated with heat transfer inside the solid adsorbent bed and it is inversely proportional to the effective conductivity.

The lack of good contact between the metal surface and the adsorbent creates a steep thermal gradient at the interface. The inefficient heat exchanger is mainly due to the shape of the adsorbent particles, generally spheres or cylinders, which do not allow a good contact between the adsorbent solid surface and the metal of the heat exchanger. In order to reduce this thermal resistance, a suitable shape of the solid bed with a smooth surface should be sought [26]. The second one is associated with heat transfer inside the adsorbent bed and inversely proportional to the thermal conductivity of the bed. The low thermal conductivity of the adsorbent bed limits the efficiency of the adsorption heat pumps. Although many efforts were made to

Table 3
Thermal conductivity (λ) and wall heat transfer [28]

	CH_3OH vapour	H_2O vapour	NaX anhydrous grain	AC35 anhydrous grain	NaX–H_2O	AC35–CH_3OH fixed bed
λ (w/m k)	0.016	0.017	0.18	0.54	0.09–0.12	0.17–0.12
h_w (w/m^2 k)	–	–	–	–	30	50

improve the thermal conductivity of the system, none of them proved to be on the right track. As a result of these studies, the following conclusions have been pointed out [27]:

- it is useless to put metallic spheres or strips into the bed;
- binders and additives (e.g. graphite) with good thermal conductivity or metallic foam must be well bound with adsorbent powder;
- the connection between grain and grain, also inside a brick, must be as large as possible; and
- consolidated samples (like bricks) must be used.

In Tables 3 and 4, it is shown some parameters which characterize the heat conductivity and the wall heat transfer.

However, a crucial point is overlooked, namely the resistance to mass transfer. The composite material compressed at high temperatures and pressures will be deprived of the high porosity necessary for a good mass transfer. It has been reported that an optimum compromise should be achieved between the high porosity necessary for fast vapor diffusion and the high density required for good thermal conductivity [29]. The resistances to mass transfer which vary in accordance with the extent of the porosity and the thickness of the adsorbent bed might play an equally important role in limiting the performance of the system. Various other designs of adsorption

Table 4
Measurements of the thermal parameters of zeolite fixed bed

	Thermal conductivity λ(w/m k)		wall heat transfer h_w(w/m^2 k)	
	Unconsolidated	consolidated	unconsolidated	consolidated
Grain	0.09	0.36	20	45
Powder+Ni foam		1.7		110
Powder+Cu foam	0.17	8.0	35	180
GNE–Zeolite in normal direction of compression	4.0	17	200	3000
GNE–Zeolite direction of compression	1	5	200	3000

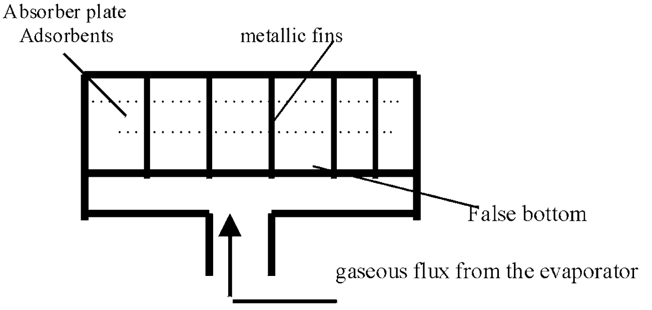

Fig. 7. Schematic of the reactor commonly used in prototypes [30,31].

heat pumps have been proposed, all aiming to improve the heat and mass transfer inside the system [30]. Most of these systems introduce new drawbacks and cannot fully achieve the desired results.

Regarding the measurement of the bed thermal conductivity, it is also evident that there are some difficulties in comparing thermal conductivity values, measured with different methods and in different conditions. The most commonly solar adsorbent bed used by many authors is shown in Fig. 7.

In order to enhance the heat transfer process, the metallic fins have been found to be very useful if they are well designed with an optimized distance between them. Mostly, the adsorptive reactor coupled to the solar collector consists of a series of copper tubes, placed side by side, making up the radiation absorber plate (Fig. 8). The porous medium occupies an annular space between the collector front surface and the axial tube formed by a metallic net where the refrigerant fluid diffuses. This model was originally proposed by Vodianitskaia and Kluppel [55] for a water silica gel cooling system, but its use has been recently described in the literature with an AC–methanol pair by Antonio Pralon Ferreira Leite and Michel Daguenet [32]. The two main advantages of the multi-tubular reactor are the simplicity of its construction and its capacity of standing pressure differences with thinner walls, considering that the system operates under vacuum.

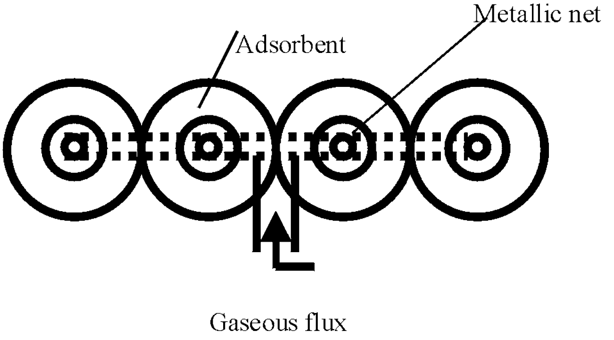

Fig. 8. Gaseous flux.

In order to improve the collector's performance and to obtain temperature up to 100°C, a selective coating for the absorber surface and a polycarbonate honeycomb as transparent insulation material (TIM) were incorporated based on the experimental study carried out by Rommel and Wagner [33]. An air gap between the absorber and TIM was considered to reduce the heat transport by conduction and by radiation. Shutters were provided to allow the collector's airing during the night, helping the heat dissipation from the adsorption reaction. A general view of the component reactor solar collector is shown in Fig. 9.

Thermosyphons and heat pipes are one of the most convenient heat transfer devices for the solid and liquid sorption machines due to their flexibility, high thermal efficiency, cost-effectiveness and reliability. Vapor-dynamic thermosyphons are capable of transporting heat up to 10 kW and more for the distance 50–100 m, which is difficult to achieve using conventional thermosyphons, horizontally disposed. In order to avoid the flooding limit and increase the maximum performance, the vapor-dynamic thermosyphons have a tube separator inside used as a vapor conduct and a two-phase coaxial annular channel around this separator where the vapor condensation is produced with high efficiency. Another important heat transfer component is a budgeting coaxial condenser with the vapor channel inside and the two-phase coaxial channel around the vapor channel.

Two-phase thermal devices which could be used as a heater and cooler alternatively for one or another supplier, heated in the evaporation zone by a constant energy source (solar, electric) and cyclically cooled in the condenser zone, are convenient for cyclic systems such as solid sorption refrigerators. They are new and need to be analyzed. A new vapor-dynamic thermosyphon of this type — thermally connected with a solar concentrator has been designed and tested. The solar energy generated by this thermosyphon was alternatively supplied to one or another adsorber [16].

The solid sorption refrigerator utilizes a solar collector (mirror), two sorbent bed canisters, connected by the heat recovery loop, a two phase heat transfer system

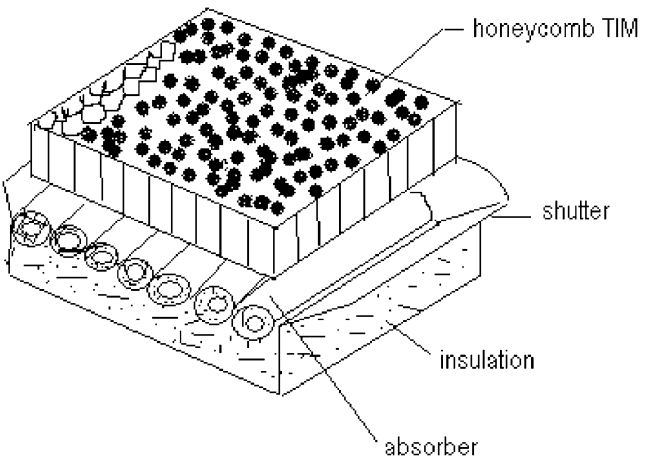

Fig. 9. General schematic view of the reactor/solar collector.

(vapor-dynamic thermosyphon), one condenser, two evaporators, and two cold panels (loop heat pipes) positioned inside the refrigerator cabinet. The solar concentrator is made from an aluminum plate as a tray (TV parabolic antenna) of diameter 1.2–1.8 m; the inner surface is covered by metallic polymer film with a high degree of reflection 0.68 (mirror) (Fig. 10).

6. Design problems and adsorption chillers

In addition to the environmental benefits of replacing CFCs and HCFCs, adsorption systems can potentially be designed to be more efficient than current systems. Compression refrigeration systems require electricity or mechanical energy to run, whereas adsorption systems can be built to run on thermal energy alone. The mechanical compressor is replaced by adsorbent beds which are used to create the pressure changes needed to drive a condensation/evaporation.

The coupling of a heat exchanger reactor to other components such as the evaporator and the condenser is one of the most important design aspect to be studied. One proposal is to use the adsorbent bed container as the evaporator–condenser heat exchanger surface [34]. In this the vapor paths are very short and the refrigerant vapor can move in a straight line to the condensing surface and vice versa; as a consequence small pressure drops occur on the vapor side. The volume of the evapor-

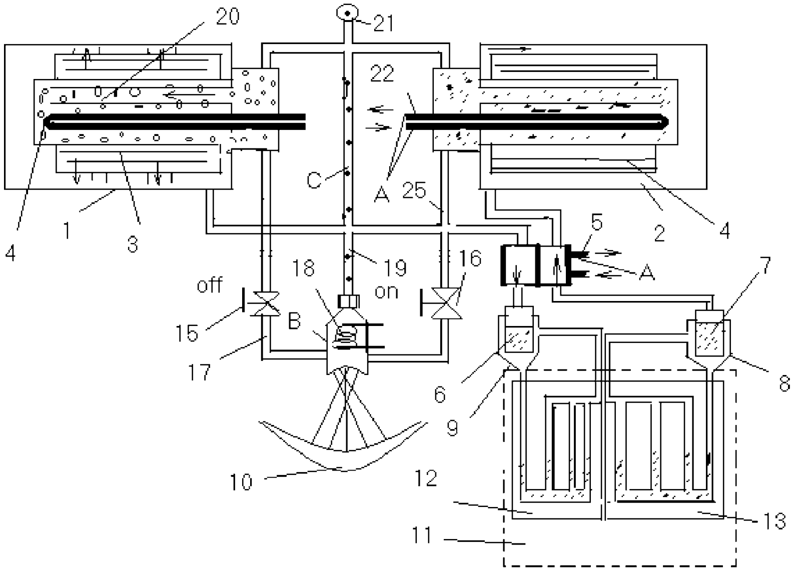

Fig. 10. Schematic diagram of the solar sorption refrigerator. 1, 2, Adsorbers; 3, 4, sorption beds; 5, condenser; 6, 7, porous evaporators; 8, 9, condensers of the spaghetti heat pipes; 10, parabolic solar concentrator; 11, refrigerator chamber; 12, 13, spaghetti heat pipes; 14, 22, elongated cylindrical condensers; 15, 16, electrical valves; 17, 24, 25, flexible liquid pipes; 18, electric cartridge heater; 19, vapour pipe; 20, vapour channel inside the condenser of the two phase heat transfer device; 21, pressure gauge.

ator and condenser components can also be reduced and a cheaper system be obtained. Another solution uses an external evaporator and condenser that are alternatively connected with the reactor [35]. In this case, valves are needed between the components. Another important aspect related to the machine design is the suitable material for each component. The most common materials currently used are: plastics; aluminum; stainless steel; and copper.

Plastics are suitable for pipes or valves but are not convenient for high temperature components like reactors because leakages could occur and maintenance would be frequently required. Aluminum is not convenient because of corrosion problems and the long term performance diminishing, especially when methanol is used as the refrigerant [36]. The same corrosion problems appear using copper with exhausted gas as the external heat vector or with refrigerants like ammonia or methanol.

The most diffuse and suitable material is stainless steel, which can be used without drawbacks in many components.

In addition to the environmental benefits of replacing CFCs and HCFCs, adsorption systems can potentially be designed to be more efficient than current systems.

Adsorption cooling is generally possible where a chilling capacity can be used for air-conditioning, process cooling etc. and where a lower temperature heat source is available, for example, from waste heat, district heating or solar energy. The existing conventional chilling capacity can be increased with no significant increase in electricity consumption. A 100 kW Mycom adsorption chiller [37] is currently being installed for municipal services at Remscheid, Germany. Seventy-five percent of the main driving heat will be supplied by solar collectors, while the remaining heating energy will be supplied by district heating. The projected system has a nominal chilling capacity at a chilled water temperature of 10°C and a hot water temperature of 70°C. The chilling process begins with a hot water temperature as low as 55°C. The adsorption refrigerator has three operational modes that form a continuous cycle. The performance and operating conditions are detailed in Table 5.

Another Japanese company, Nishydo, has installed a 320 kW silica gel adsorption unit in a shopping center, Koningsgalerie in Kassel, Germany, parallel to a conventional 260 kW chiller, supplying peak chilling capacity only. Seventy-eight percent of the annual chilling demand (450 MWh) is realized by the adsorption chiller.

At a noodle-making factory in Japan, a Mycom adsorption refrigerator (106 kW) is installed in the CHP (combined heat and power) system of a diesel-engine-driven chiller unit and electric power generator. All the electricity required to run the system is generated by the system itself. The adsorption refrigerator is driven by both the waste exhaust heat from the engine and the waste warm water (72°C) from the noodle production line. The adsorption refrigerator cools the water from 21°C to 16°C. A conventional unit then cools the water further, to a temperature of 5°C, in order to cool the noodles. Implementing this system means that the capacity of the conventional chiller is increased by 45%.

In the case of solid sorption, silica gel is taken if a commercial chiller is to be utilized. One of the drawbacks of solid sorption systems compared with liquid sorption systems is their inherent need to store sorbent and consequently heat or cold [38].

7. Operating considerations and energy storage

An obvious complement, depending on the relative economics, is energy storage. For the specific end-use of cooling, one can store the energy of collected sunlight as ice. Ice storage offers the advantages of compactness (relative to any form of sensible heat storage) safety and low expense.

Generally speaking, the main problem of solar cooling is a storage problem — in many applications temperatures at night allow for effective cooling, but some cold has to be saved for the daytime. A solution might be a water store chilled by nighttime radiation. A more compact storage would be achieved with ice, but to this end a real chiller is required. This is a typical application for the solid sorption solar assisted storage systems.

The length of the cycle is a very important parameter strongly affecting the operation of gas–solid systems.

Different cycle lengths are needed for different applications; typical values of a few minutes are necessary in applications such as rotating system or similar; while cycles of 1–3 h have been operated in a demonstration plant utilizing 150 kg of zeolite located in two 'isothermal' reactors [39]. Short cycles can be obtained by a multibed system with internal heat recovery.

8. Market aspects

In the air-conditioning sector the most important users' request is a high probability that the system will satisfactorily perform its intended function without need

Table 5
Capacity and operating conditions

	Model No.	ADR-20	ADR-30	ADR-100
Hot water	T_{in} (°C)/T_{out} (°C)	75/70	75/70	75/70
	Flow rate (m^3/h)	20	30	101
	Used heat (kW)	120	180	590
Cooling water	T_{in} (°C)/T_{out} (°C)	29/33	29/33	29/33
	Flow rate (m^3/h)	41	62	205
	Cooling load (kW)	190	290	960
Chilled water	T_{in} (°C)/T_{out} (°C)	14/9	14/19	14/9
	Flow rate (m^3/h)	12	18	61
	Chilling capacity(kW)	70	106	352
COP	–	0.6	0.6	0.6
Cooling water pump (kW)	–	3.7	5.5	18
Refrigerant pump (kW)	–	0.3	0.3	0.6
Vacuum pump (kW)	–	0.3	0.4	0.8
Operating weight (ton)	–	7.5	11	25
Dimensions (m×m×m)	–	2.4×2.1 ×2.8	3.1×2.2×2.8	6.3×3.1×3.5

for frequent maintenance, that is, to be reliable. Also important are the economic effectiveness and the need for reduced noise and air pollution.

From this point of view the gas–solid systems have the possibility of fully satisfying users' requests; in fact, no noisy components such as compressors are used in the system; pumps are used but their noise level is very low. For domestic applications this feature makes solar adsorption systems very attractive, especially when compared with compressor heat pumps and cooling systems [39]. Other market demands are:

- the system must be easy to use so as to operate without problems;
- the system must need low maintenance in order to reduce the operating cost;
- the capacity of the system must be easy to regulate; and
- the system must have a storage capacity, especially for cooling applications.

9. Conclusion

From this review one can conclude that the possibility of using non-polluting materials and to save more than half of the primary energy involved in this sector are obviously the most important characteristics but simplicity, low maintenance and the absence of noisy components are also very important features that make this type of system suitable for numerous other applications such as air-conditioning in cars, trains, bus or food transportation or solar cooling.

Although investment costs for adsorption chillers using silica gel are still around EUR 500/kW the environmental benefits are impressive, when compared to conventional compressor chillers. The absence of harmful or hazardous products such as CFCs, together with a substantial reduction of CO_2 emissions due to very low consumption of electricity, creates an environmentally safe technology. Low-temperature waste heat or solar energy can be converted into a chilling capacity as low as 5°C with minor maintenance costs.

It is also important to have for each different application of cooling an optimum combination of collector and cooling system that matches the special cooling demand and also the constraints of the available solar radiation in the best way, with only a marginal need for assistance from fossil fuels.

Nevertheless, some crucial points in the development of sorption systems still exist and they are those are closely connected to the low specific power of the machine and the investment costs.

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